

Local and Global Radiative Feedback from Population III Star Formation

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Abstract. We present an overview of recent work that focuses on understanding the radiative feedback processes that are potentially important during Population III star formation. Specifically, we examine the effect of the Lyman-Werner (photodissociating) background on the early stages of primordial star formation, which serves to delay the onset of star formation in a given halo but never suppresses it entirely. We also examine the effect that both photodissociating and ionizing radiation in I-fronts from nearby stellar systems have on the formation of primordial protostellar clouds. Depending on the strength of the incoming radiation field and the central density of the halos, Pop III star formation can be suppressed, unaffected, or even enhanced. Understanding these and other effects is crucial to modeling Population III star formation and to building the earliest generations of galaxies in the Universe.

Keywords: Population III stars, reionization, radiative feedback, high redshift structure formation

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INTRODUCTION

Population III star formation is generally considered to be a simple problem compared to galactic star formation. This is only strictly true, however, for the so-called “Population III.1” stars, which form in the absence of any non-cosmological influences [1, 8]. Our current understanding is that the transition from Pop III to metal-enriched star formation occurs very quickly locally, but globally this transition extends over a wide range of redshifts (possibly down to $z \sim 6$). As a result, the vast majority of Population III stars will form in a universe where earlier generations of primordial and metal-enriched stars have produced both photodissociating and ionizing radiation, as well as X-ray, cosmic rays, and kinetic feedback.

This feedback could very possibly affect the final mass of the primordial stars, and stars that form under these conditions are often referred to as “Population III.2” stars. [1] This term is somewhat misleading, because it implies homogeneity in the effects of these various types of feedback. This is incorrect. Lyman-Werner radiation ($E_\nu \sim 11.18 - 13.6$ eV) photodissociates molecular hydrogen, which typically delays star formation. Ionizing radiation destroys H_2 and ionizes hydrogen, which in principle completely halts star formation; however, massive stars are short-lived, and the huge free electron populations in relic HII regions can catalyze tremendous amounts of H_2 and HD formation, possibly spurring primordial star formation and changing the characteristic mass scales of these stars. X-rays and cosmic rays most likely also promote the

creation of a significant free electron population, catalyzing H_2 and HD formation and accelerating primordial star formation. To further complicate matters, a single star (or stellar population) produces multiple types of feedback whose net effect depends heavily on the relative positioning of halos and cosmic epoch. One can safely say that the majority of Population III stars form in situations where the feedback acting upon them is context-sensitive and the final outcome is ambiguous. In this paper, we present studies of the effects of a global photodissociating background on a primordial star-forming halo, and, separately, multifrequency radiation hydrodynamics simulations of impinging ionization fronts on idealized cosmological halos.

EFFECTS OF A GLOBAL PHOTODISSOCIATING BACKGROUND

In order to study the effects of a global photodissociating background, we take a single “standard” Pop III star formation simulation using the Enzo code [4, 2] and gradually increase the strength of the Lyman-Werner (H_2 photodissociating) background. Other than the strength of the photodissociating background, all other simulation parameters (as well as the initial conditions) are kept constant.

Figures 1 and 2 show the primary results from this work, which are examined in much more detail in [5]. Figure 1 shows the effect that turning up the FUV background has on the halo collapse redshift, virial mass of the halo, and virial temperature of the halo. In general, raising the strength of the photodissociating background delays Population III star formation to lower redshifts, when the halo is more massive and hotter. The FUV background only delays star formation – it is never completely suppressed, because a small amount of molecular hydrogen can always form. Figure 2 shows the estimated accretion of gas onto the protostellar core based on conditions at the time where the gas finally collapses to high densities in each of these simulations. In general, simulations with larger FUV backgrounds are hotter, and since the inflow of gas occurs at approximately the sound speed in the halo, the accretion rates are higher. A naive reading of this figure implies that Pop III stars in the presence of a FUV background are more massive, but detailed semi-analytical models suggest that this may not actually be so [7, 8].

LOCAL EFFECTS OF IONIZING RADIATION

Cosmological simulations [3, 11] suggest that HII regions from nearby massive stars may delay primordial star formation in a neighboring halo, but the residual electron population after the death of the original star will ultimately make more H_2 and HD than would be possible in an undisturbed halo. The major issue with these cosmological simulations is that they very loosely approximate I-front interactions with gas in neighboring halos, using static density fields and assuming monochromatic incident radiation. These two assumptions seriously limit the validity of the results from such calculations.

In the study presented here (originally published in [9, 10]), we use idealized simulations that combine multifrequency radiation transport with non-equilibrium chemistry, hydrodynamics, and radiative cooling. Ionization fronts have finite widths, with

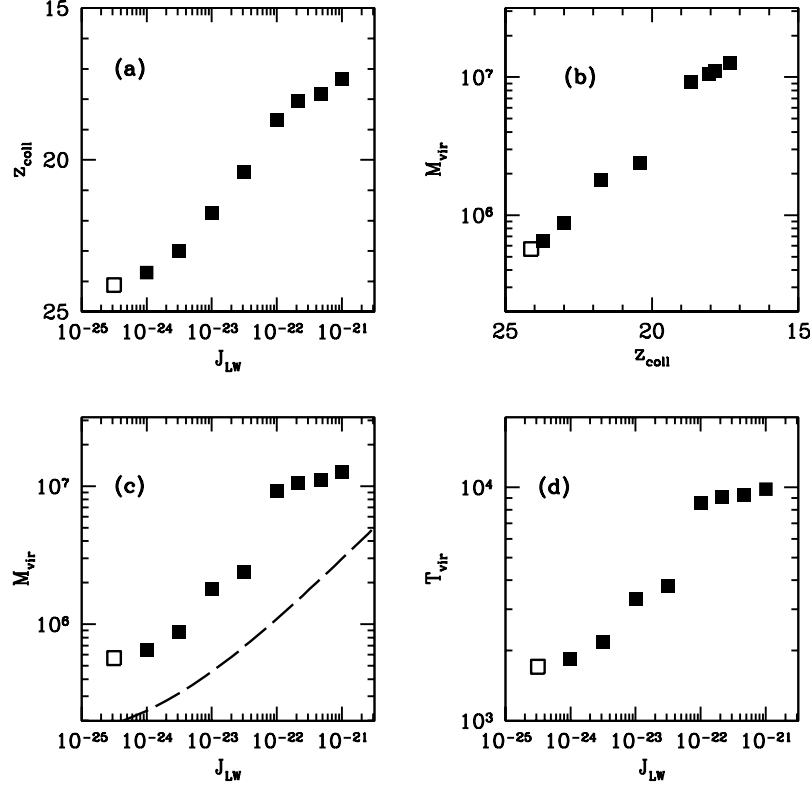


FIGURE 1. Mean halo quantities for several simulations with the same cosmic realization but a range of Lyman-Werner molecular hydrogen photodissociating flux backgrounds. Panel (a): J_{LW} vs. halo collapse redshift. Panel (b): halo virial mass vs. halo collapse redshift. Panel (c): halo virial mass vs. J_{LW} . Panel (d): halo virial temperature vs. J_{LW} . The $J_{21} = 0$ “control” results are shown as an open square (and is at $\log J_{LW} = -24.5$ in the panels which are a function of J_{LW}). In the bottom left panel, the dashed line corresponds to the fitting function for threshold mass from [12], Eqn. 8. Figure is from [5].

H_2 -photodissociating radiation and X-rays generally traveling ahead of the ionizing radiation. This is particularly true in Population III stars, where the surface temperatures are extremely high. In this proceedings we present results from [10], which focuses on I-fronts from Pop III stars with masses of $15\text{--}40 M_{\odot}$. A grid of simulations are performed, varying both the central number density of an idealized $1.35 \times 10^5 M_{\odot}$ halo and the distance between the star and the density peak of this halo (and, thus, the intensity of incident radiation at the halo).

Figure 3 shows the distribution of baryons at the end of a representative simulation with a high central halo density. In this case, the I-front has washed over the halo, but H_2 has formed in the relatively dense gas around the halo core and shielded it from the incident Lyman-Werner photons. Figure 4 shows the outcomes for a suite of models, varying source distance and halo central density, for two different stellar masses (and thus spectral shapes). Halos close to the star and with relatively low central densities are evacuated of gas, suppressing star formation. Halos that are further way or have higher central gas densities see either a delay in gas collapse or no effect whatsoever.

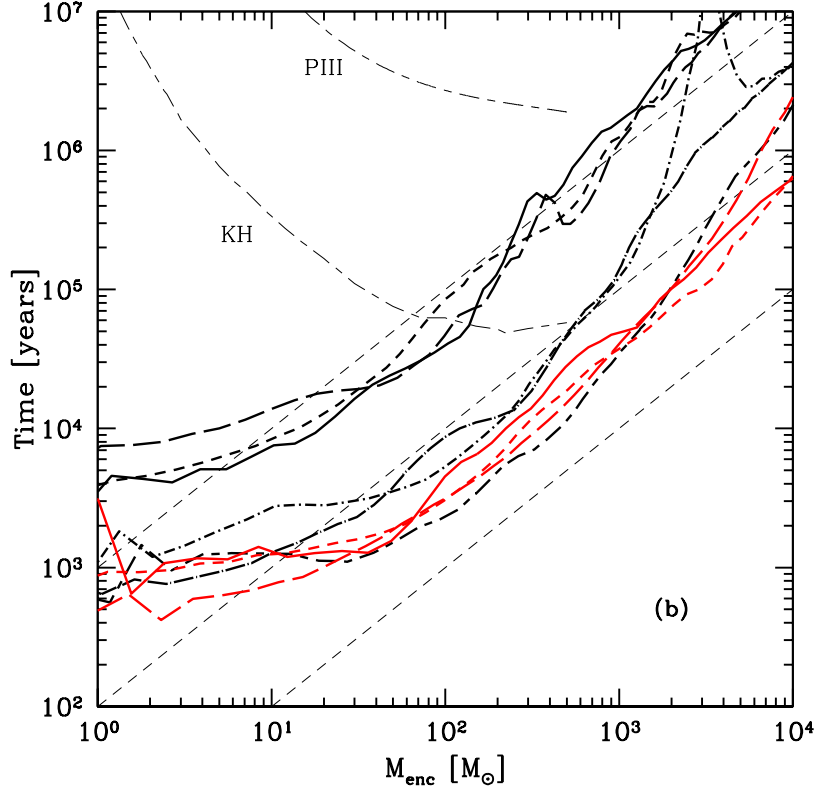


FIGURE 2. Spherically-averaged, mass-weighted accretion time as a function of enclosed baryon mass, shown at the point where the maximum baryon number density in the simulation is approximately 10^{10} cm^{-3} . Line types and weights correspond to those in Figure 9 of [5] and, from top to bottom, generally go from low to high FUV flux. The upper and lower light short-long-dashed curves which extend from the upper left corner correspond to the main sequence lifetime of a massive Population III star of that mass and the Kelvin-Helmholtz time scale of a Population III time scale with a given luminosity and radius. All values are taken from [6]. The three light diagonal short-dashed lines which extend from bottom left to top right correspond to masses accreted using constant accretion rates of (from top to bottom) $\dot{m} = 10^{-3}$, 10^{-2} , and $10^{-1} \text{ M}_{\odot}/\text{yr}$. Figure is from [5].

The outcomes are much less clear-cut than in the situation where we examine the effect of a photodissociating background alone – depending on the central baryon density and strength of the incoming radiation background, halos can be completely evaporated, have delayed star formation, or be completely unaffected.

DISCUSSION AND CONCLUSIONS

The vast majority of primordial stars do not form in splendid isolation – the evolution of the protostellar gas clouds that will become Population III stars can be strongly influenced by radiation created by the previous generations of star formation. Depending on the circumstances, this feedback can have a variety of outcomes. It appears that photodissociating radiation can never completely halt the formation of molecular hydrogen

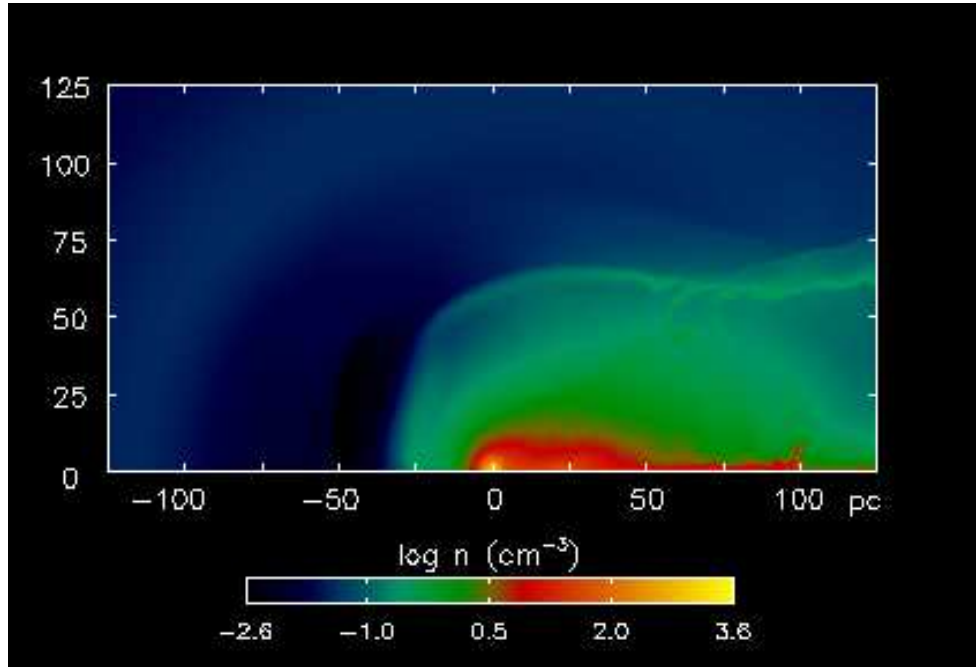


FIGURE 3. Evaporated halo with $n_c = 1596 \text{ cm}^{-3}$, 150 pc from a $60 M_\odot$ star at 10 Myr. The core of the halo is slightly displaced to the left of center by backflow from the collapsed shadow on the right. Figure from [10].

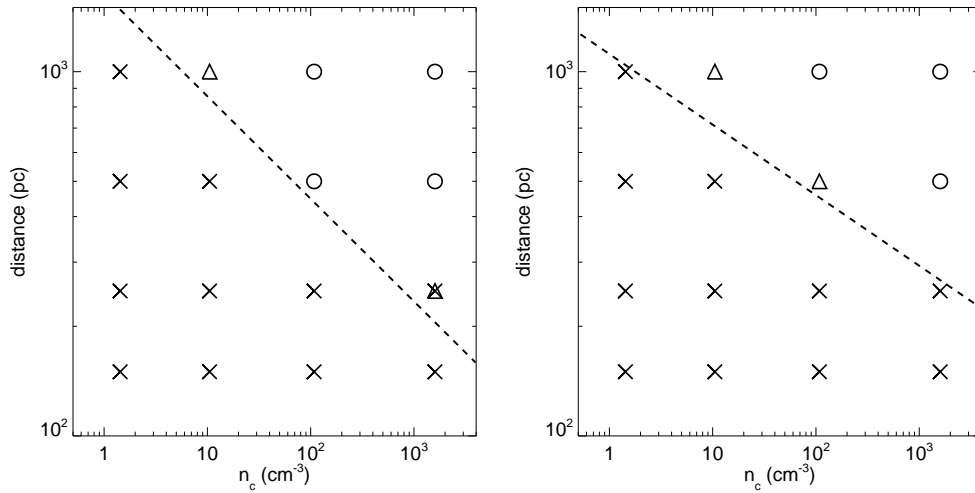


FIGURE 4. Radiative and kinetic feedback on star formation near a $25 M_\odot$ star (left) and a $40 M_\odot$ star (right). Completely evaporated halos with no star formation are labeled by crosses, while halos with delayed or unchanged star formation are marked by triangles and circles, respectively. The triangle overlaid on the cross in the $25 M_\odot$ panel signifies that the halo can form a delayed star if the SN goes off in the $6.9 \times 10^5 M_\odot$ halo but not if it is in the $2.1 \times 10^6 M_\odot$ halo. The dotted lines again define the boundary for star formation in the evaporated halos, above which it proceeds and below which it is quenched. Figure from [10].

in $T_{\text{vir}} < 10^4$ K halos, and can only delay the formation of a primordial star in a given halo, until the halo has grown sufficiently for the small amount of H_2 in it to be an efficient coolant. FUV background only delays, and never completely suppresses, H_2 formation and thus Pop III star formation. This appears to be a robust result: Machacek et al. [12] suggested that the FUV background imposes a threshold mass for star formation that rises with the strength of the FUV background, and, separately, Wise & Abel [13] show that, even with very high FUV backgrounds, collisional ionization drives H_2 formation faster than it can be dissociated.

The interaction of ionization fronts with a primordial halo can have a variety of effects, from completely evaporating the halo to having no influence on its star formation whatsoever. It is clear that in order to accurately investigate these effects one needs multifrequency radiation hydrodynamics simulations. Furthermore, it seems critical to move beyond the tiny simulation volumes and single stars that are typically used in Pop III star formation, and to instead simulate more realistic circumstances: high-sigma peaks at high redshift (corresponding to clusters of halos), and lower-sigma peaks at all redshifts, both with appropriate radiation backgrounds. Only when we study a much wider variety of potentially star-forming primordial halos can we understand Population III star formation and how early stellar populations regulate their own growth.

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